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RESEARCH MEMORANDUM

EVALUATION OF THREE INJECTORS IN A 2400-POUND-THRUST ROCKET ENGINE USING LIQUID OXYGEN AND LIQUID AMMONIA

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EVALUATION OF THREE INJECTORS IN A 2400-POUND-THRUST ROCKET ENGINE USING LIQUID OXYGEN AND LIQUID AMMONIA*

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SUMMARY

The performance of three injector types was evaluated in a 2400-pound-thrust rocket test chamber. Each injector represents one of eighteen such units forming the injector for a 50,000-pound-thrust rocket engine. The injectors were designed to compare the relative effects of fuel and oxidant atomization.

Characteristic velocity and specific impulse were obtained over a range of oxidant-to-fuel ratios at a nominal chamber pressure of 600 pounds per square inch absolute. Injectors atomizing the fuel (RMI-1 and RMI-2) gave comparable results. No stabilized data were obtained with the injector atomizing the oxidant only (RMI-3) because of combustion instability. The unsteady-state data indicated that the performance of this RMI-3 injector was lower than RMI-1 and RMI-2. For the thrust-chamber configuration used, combustion instability was not encountered with the RMI-2 injector, but incipient combustion instability was encountered with the RMI-1 injector.

INTRODUCTION

At the request of the Air Force, the NACA Lewis laboratory investigated the performance of three types of injector spuds, or elements, designed by Reaction Motors, Inc. for use with the oxygen-ammonia propellant combination. These spuds, in groups of 18, are designed for application in a backup version of the injector for the XLR99-RMI-1 engine. The three injectors investigated were designed to represent the relative contribution of fuel and oxidant atomization to engine performance. The evaluation was based on the performance of injectors featuring fuel atomization, oxidant atomization, and both fuel and oxidant atomization. Characteristic velocity and specific impulse were determined for each of the injector types from tests of a single spud mounted in a 2400-pound-thrust rocket chamber.

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*Title, Unclassified.

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APPARATUS, INSTRUMENTATION, AND PROCEDURE

Apparatus

Injectors. - The three injectors evaluated are shown in figure 1. Injector RMI-1 consisted of 22 pairs each of like-on-like fuel and oxidant holes with surface impingement at 90°. Injector RMI-2 consisted of 22 pairs of like-on-like fuel holes with surface impingement at 90° and 22 showerhead oxidant holes. Injector RMI-3 consisted of 22 pairs of like-on-like oxidant holes with surface impingement at 90° and 22 showerhead fuel holes.

The injectors were made of nickel "A." The oxidant injection holes were fed from a reservoir on the upstream side of the injection face. The fuel injection holes were fed by passages, cross-drilled through the injector, from a fuel manifold around the circumference of the injector. The injector was designed to deliver 6.1 pound-mass per second oxidant and 4.9 pound-mass per second fuel at an injector pressure drop of 189 pounds per square inch. Fuel coolant holes were provided in the basic design; however, they were eliminated during the course of the experiments to prevent face burning.

Injector holders. - The injector holders (figs. 2 and 3) were made from stainless steel and were designed to provide a fuel manifold, an oxidant reservoir, and flanges for mounting to the thrust stand. The original design provided for the removal of the injector from the holder; it utilized a small bottoming lip for positioning, and two O-rings for sealing the fuel from the chamber and the atmosphere. The injector was brazed to a tube which was in turn screwed into position in the holder. However, this holder (A) burned on the flat face surface (fig. 2(a)). In an attempt to eliminate this burning, a modification was made as shown in figure 2(b); but this modified holder (B) also burned. A further modification to the holder was made after a severe fuel leakage into the chamber caused immediate burnout; this modification (holder C) is shown in figure 2(c). Although holder C did not leak, the edge of the insert burned. The next step was to eliminate the fuel coolant holes around the periphery and mount the injector flush in the chamber. Two of these holders (type D) were used for RMI-1 and RMI-3 injectors, and a redesign was used with RMI-2. This modification (holder D) is shown in figure 3.

Description of chamber and nozzle. - The thrust chamber was a $5\frac{1}{2}$-inch-outside-diameter mild steel pipe, bored to a 4.072-inch inside diameter. The chambers used with holder modifications A, B, and C were $7\frac{9}{16}$ inches in length. The chamber used with holder D was 8 inches in length. The chamber-pressure taps were installed near the injector and the nozzle (fig. 3). The nozzles were made of copper, chromium-plated (0.003 to 0.005 in. thick), and of mild steel, ceramic-coated (0.010 to 0.020 in. thick). The nozzle had a throat area of 3.259 square inches and a 4-to-1 contraction ratio. The throat extended 0.125 inch downstream; the divergent section was eliminated. Eight bolts were used to compress the metal O-ring seals and hold the assembly together (fig. 3).

Instrumentation

The engine was mounted on a flexure-plate thrust stand equipped with a strain-gage force-measuring load cell. Chamber pressure was measured both with strain-gage transducers and with a recording Bourdon-tube instrument. To obtain stable recording conditions during the short duration runs, short water-cooled pressure leads to the pickup were used to decrease the time lag. Oxidant and fuel flow were each measured with two instruments, a turbine-type flowmeter and a Venturi meter equipped with a differential pressure transducer. These signals were recorded by an oscillograph. Accuracies of the load cell, pressure transducers, flowmeters, and recording oscillograph were rated at ±1 percent or better.

Temperatures of the liquid oxygen were measured by copper-constantan thermocouples with cold-junction thermocouples in a bath of liquid nitrogen. The copper-constantan thermocouples were made from calibrated wire with a line drop of 3 microvolts or less. The ammonia temperatures were recorded by iron-constantan thermocouples with cold-junction thermocouples located in a bath of melting ice. Temperatures were recorded on the aforementioned recording oscillograph and on strip-chart recording potentiometers. An accelerometer, installed on the engine to determine whether or not screaming occurred, responded to radial accelerations caused by pressure oscillations within the chamber. The signal from the accelerometer was received by an oscilloscope and recorded on film.

Calibrations. - The pressure transducers were calibrated before each series of runs with helium gas and standard gages with accuracies rated at ±1/4 percent. The thrust-measuring load cell was also calibrated before each run by using a standard load cell with a rated accuracy of ±1/4 percent. The constants of calibration varied between the series of runs about $\pm 2\frac{1}{4}$ percent for the pressure transducers and $\pm 5\frac{1}{2}$ percent for the thrust-measuring load cell.

The thermocouples were calibrated prior to the series of runs, and check points were made intermittently to assure that the calibration constant did not vary.

Errors in measuring performance. - Although the instrumentation was rated at ±1 percent or better, there were several errors that reduced the accuracy of performance measurements. Difficulties that were experienced in measuring oxygen temperature increased the error in determining oxygen mass flow. The thrust load cell was used at half capacity. Errors were observed in combustion-chamber pressure, probably from thermal effects on the diaphragm of the strain-gage pressure transducers. The maximum error in measuring specific impulse and characteristic velocity was estimated to be ±5 percent.

Operational Procedure

A flow diagram of the test facility is shown in figure 4. The engine was started with gaseous oxygen and gaseous propane fed at relatively low pressures (50 and 30 lb/sq in. gage, respectively) through the injector. These propellants were ignited by a torch located outside the nozzle. After ignition of the gases occurred in the chamber, the main propellant valves were opened to obtain approximately 20 percent of full flow. After 1.5 seconds of this low propellant flow, the valves were opened to full flow. Full propellant flow was maintained for periods of time ranging from 2 to 3 seconds, with one run of 7 seconds recorded for the RMI-2 injector.

The propellant tanks were pressurized to 975 pounds per square inch gage for the fuel and 1000 pounds per square inch gage for the oxidant. The propellant flows were regulated by positioning the propellant valves.

RESULTS AND DISCUSSION

Thirteen runs were made with RMI-1, seventeen runs were made with RMI-2, and three runs were made with RMI-3. The performance data obtained are shown in table I and are plotted in figures 5, 6, and 7.

The experimental performance characteristics of injectors RMI-1 and RMI-2 were comparable within the accuracy of the measurements. Steady-state performance figures are unavailable for the RMI-3 injector because of combustion oscillations that limited the run duration to less than 1 second. The unsteady-state data indicated that the performance of this injector was lower than RMI-1 and RMI-2. In general, the experimental performance data were scattered as a result of errors previously mentioned. The curves obtained by linear regression (figs. 5 and 6) indicated the characteristic-velocity standard error of estimate to be ±186 feet per second for RMI-1 and ±133 feet per second for RMI-2. The specific-impulse standard error of estimate was ±7 seconds for RMI-1 and ±2 seconds for RMI-2.

The curves indicated the characteristic velocity to be 87 percent of theoretical for RMI-1 and 89 percent of theoretical for RMI-2 at an oxidant-fuel weight ratio of 1.25. The specific impulse was 82 percent of theoretical for RMI-1 and 84 percent of theoretical for RMI-2 at an oxidant-fuel weight ratio of 1.25.

Because of insufficient data, the regression line was not computed for RMI-3.

In the engine configuration used, the effect of oxygen atomization on performance appeared to be small. The importance of ammonia atomization was not determined. Similar studies with ammonia-oxygen (ref. 1), hydrocarbon-oxygen (ref. 2), and hydrocarbon-oxygen-fluorine (ref. 3) have been made at a 200-pound-thrust level. These studies have shown engine performance to be dependent on the atomization of the least volatile propellant, which in the present investigation would be the ammonia. The previous studies also showed that the performance obtained by atomizing the ammonia was lower than that obtained by atomizing the hydrocarbon. This indicated that, with the ammonia-oxygen combination, a greater degree of ammonia atomization is necessary to achieve comparable performance.

Operational difficulties were experienced in starting the injectors. Injector RMI-1 was the most reliable on starts. Apparently the well-atomized propellants from the like-on-like holes had less tendency to quench the ignition source. Frequent burnouts were experienced. In general, the trouble occurred on the uncooled injector-holder face. Essentially, four separate designs of injector holders were utilized in an effort to alleviate the face burning, as previously described.

Screaming was suspected on several burnouts. Accelerometer readings were made on the three types of injectors. The RMI-1 injector showed evidence of incipient screaming on transition from low flow to high flow. In all runs except one the large-amplitude vibrations dampened out after high flows were established. In the one run where no dampening occurred, the cooled holder was burned. The RMI-2 injector gave no evidence of screaming. An accelerometer record of the RMI-3 injector with holder D (fig. 3) indicated large-amplitude pressure waves. The holder and injector were badly burned.

SUMMARY OF RESULTS

Experimental investigation of the three RMI injectors showed:

1. The characteristic velocity and the specific impulse of RMI-1 and RMI-2 were comparable.

2. For the combustor configuration used, combustion instability was not encountered with the RMI-2 injector, but incipient combustion instability was encountered with the RMI-1 injector.

3. RMI-3 gave no stabilized data because of combustion instability; however, indications were that this injector had lower performance than the other two injectors.

4. Since adequate data were unavailable for the RMI-3 injector, a comparison of the effect of fuel atomization on performance was not obtained. Comparison of RMI-1 and RMI-2 showed oxidant atomization to have a second-order effect on performance.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 7, 1958

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1. Priem, Richard J., and Clark, Bruce J.: Comparison of Injectors with a 200-Pound-Thrust Ammonia-Oxygen Engine. NACA RM E57H01, 1957.

2. Heidmann, M. F., and Auble, C. M.: Injection Principles from Combustion Studies in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E55C22, 1955.

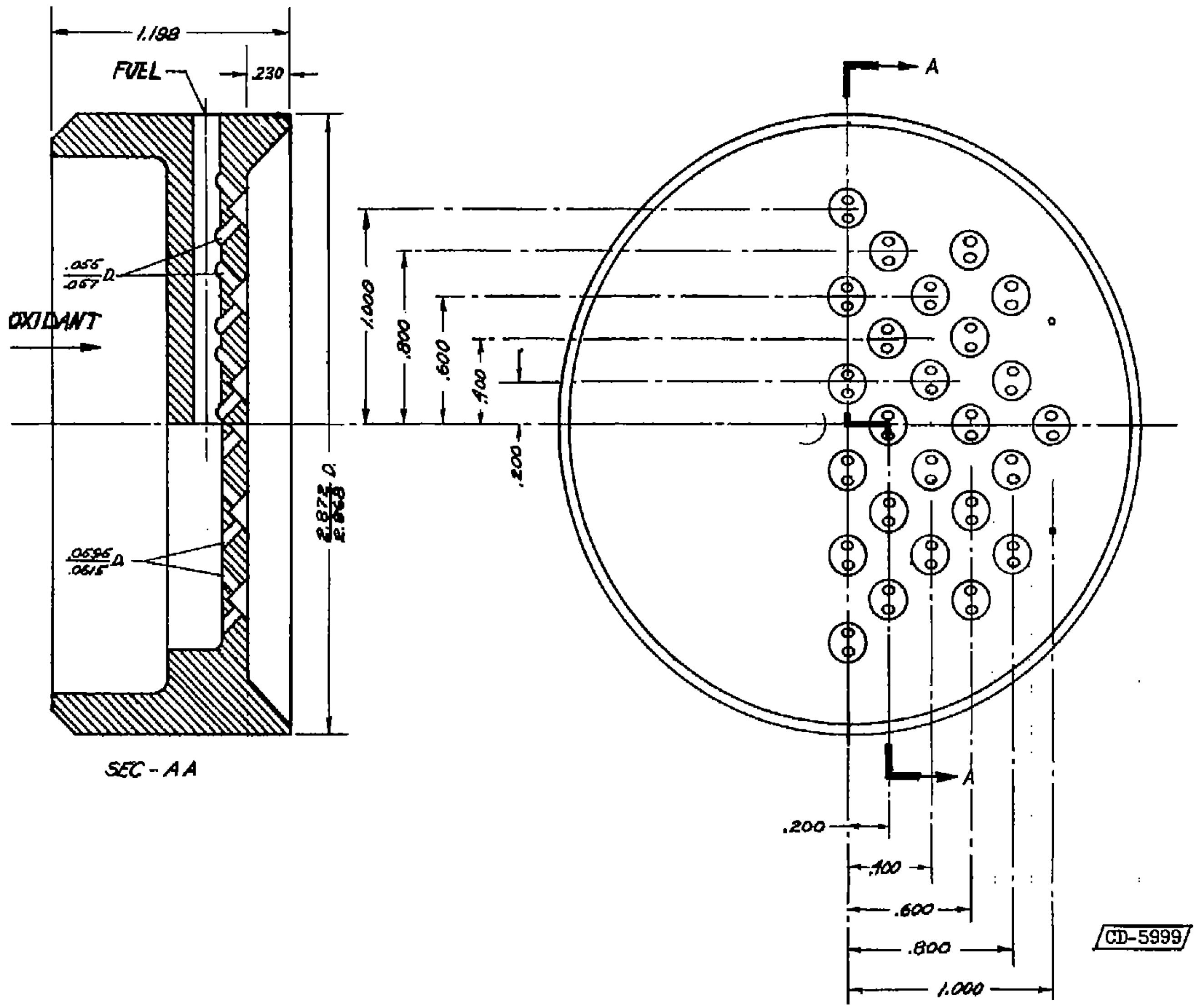
3. Heidmann, M. F.: A Study of Injection Process for 15-Percent Fluorine - 85-Percent Oxygen and Heptane in a 200-Pound-Thrust Rocket Engine. NACA RM E56J11, 1957.

TABLE I. - EXPERIMENTAL PERFORMANCE DATA FOR INJECTORS RMI-1, RMI-2, AND RMI-3

No.	Injector (a)	Reference run	Oxidant-fuel weight ratio, O/F	Specific impulse, I_s, lb-force/(lb-mass/sec)	Theoretical specific impulse, $I_{s,th}$, lb-force/(lb-mass/sec)	$I_s/I_{s,th}$, percent	Characteristic velocity, c^*, ft/sec	Theoretical characteristic velocity, c^*_{th}, ft/sec	c^*/c^*_{th}, percent	Accelerometer, cps	General remarks
1	RMI-1	372	1.218	178.4	217.4	82.1	4637.1	5805	80.0	8000-13,000	Amplitude 12½ times normal oscillations; burnout
2		371	1.269	178.2	217.5	81.9	5181.0	5819	89.0	7000	
3		370	1.258	182.7	217.5	84.0	5295.8	5812	91.1	7000-8000	
4		369	1.272	180.4	217.5	82.9	5158.4	5820	88.6	7000-8000	
5		368	1.363	172.4	217.1	79.4	5045.9	5812	86.8	7500	
6		363	1.302	169.4	217.4	77.9	5151.6	5823	88.5	7000	
7		362	1.286	167.8	217.4	77.2	5189.2	5822	89.1	5000-7000	
8		361	1.249	168.8	217.5	77.6	5061.1	5815	87.0	5000-7000	Large amplitude during transition; nearly unstable
9		360	1.239	173.1	217.5	79.6	5119.9	5812	88.1	6500	Partially unstable
10		359	1.047	173.5	215.6	80.5	5217.8	5674	92.0	5000-7000	
11		340	1.344	180.9	217.2	83.3	4946.6	5815	85.1		
12		339	1.326	184.6	217.2	85.0	5312.3	5819	91.3		
13		338	1.284	194.1	217.4	89.3	4768.2	5822	81.9		
14	RMI-2	382	1.164	189.7	217.1	87.4	5389.6	5776	93.3	6000-7500	7-Second run
15		381	1.270	186.0	217.5	86.7	5200.0	5820	89.3	5000-6500	
16		380	1.323	185.9	217.3	85.5	5155.1	5820	88.6	5000-7500	
17		379	1.318	177.5	217.3	81.7	5174.0	5821	88.9	5000-7500	
18		378	1.295	183.7	217.4	84.5	5152.7	5822	88.5	6500-8000	
19		377	1.268	185.4	217.5	85.2	5202.4	5819	89.4	6000-8000	
20		276	1.287	184.7	217.4	85.0	5112.8	5822	87.8	7000-8000	
21		375	1.330	165.6	217.2	76.2	4813.9	5817	82.8	7000	
22		374	1.458	168.7	215.7	78.2	4853.7	5758	84.3	6500	
23		373	1.546	162.4	214.4	75.7	4850.7	5683	85.4	7000	
24		347	1.328	174.6	217.3	80.3	5324.3	5819	91.4		
25		346	1.283	181.6	217.5	83.5	5439.7	5817	93.5		
26		345	1.283	179.1	217.5	82.3	5448.3	5818	93.6		
27		344	1.345	177.8	217.2	81.9	5142.3	5815	88.4		
28		343	1.333	172.6	217.2	79.5	5030.4	5817	86.4		
29		342	1.318	181.8	217.3	83.7	5111.1	5821	87.8		
30		341	1.383	176.0	216.8	81.2	4807.4	5800	82.8		
31	RMI-3	365	1.337	178	217.2	82	5141	5817	88	5000-7000	Amplitude more than 14 times normal oscillation[b]
32		364	1.547	166.6	214.4	78	4256	5706	75	5000-7000	
33		356	1.25	176	217.5	81	5031	5815	86		Burnout[b]

[a]All holder modifications are holder D (fig. 3) except for 32 and 33, where holder C (fig. 2(c)) was used.

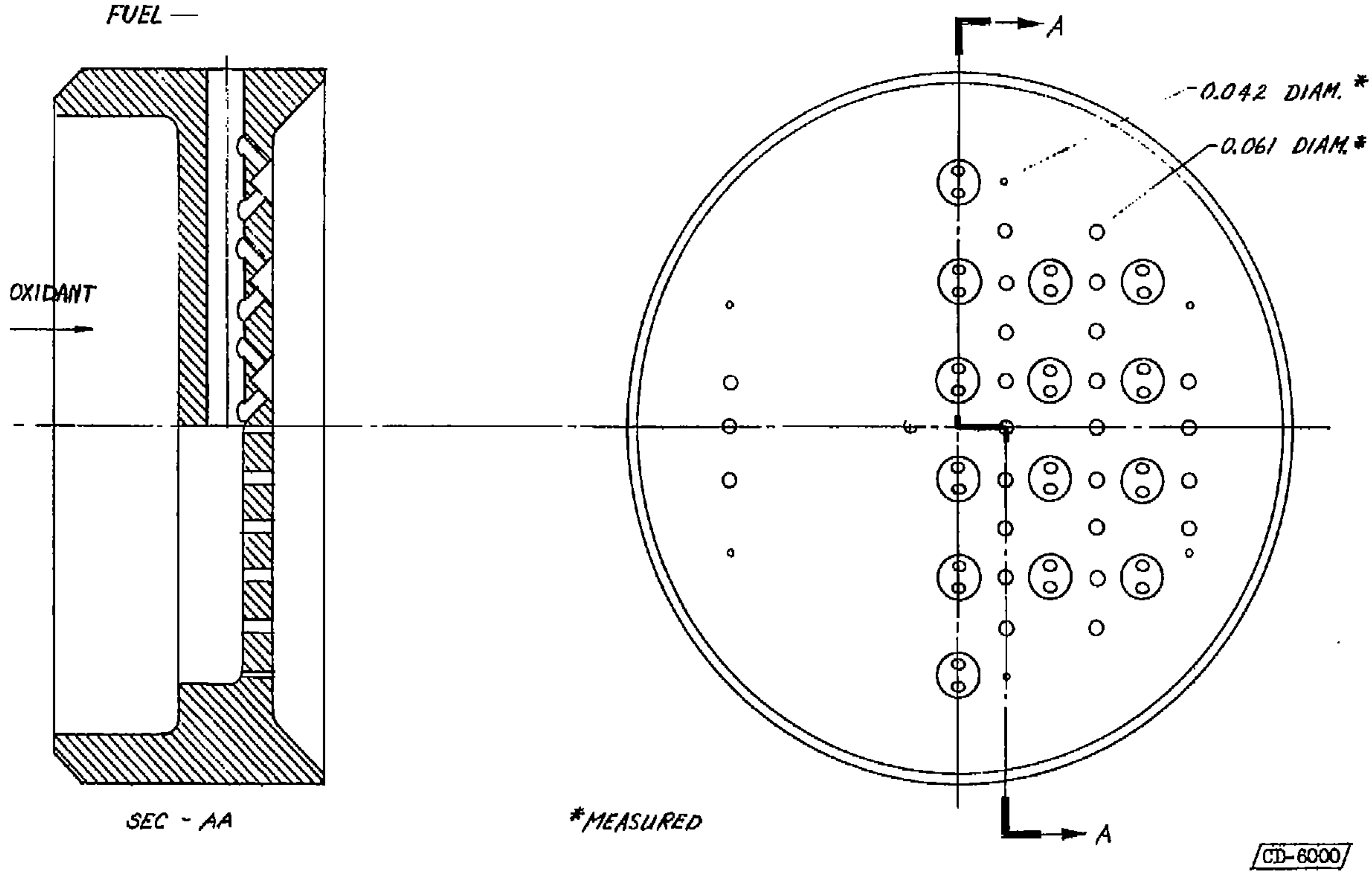
[b]Large-amplitude oscillation; immediate shutdown.



(a) RMI-1 injector; 22 pairs each of like-on-like fuel and oxidant holes with surface impingement at 90°.

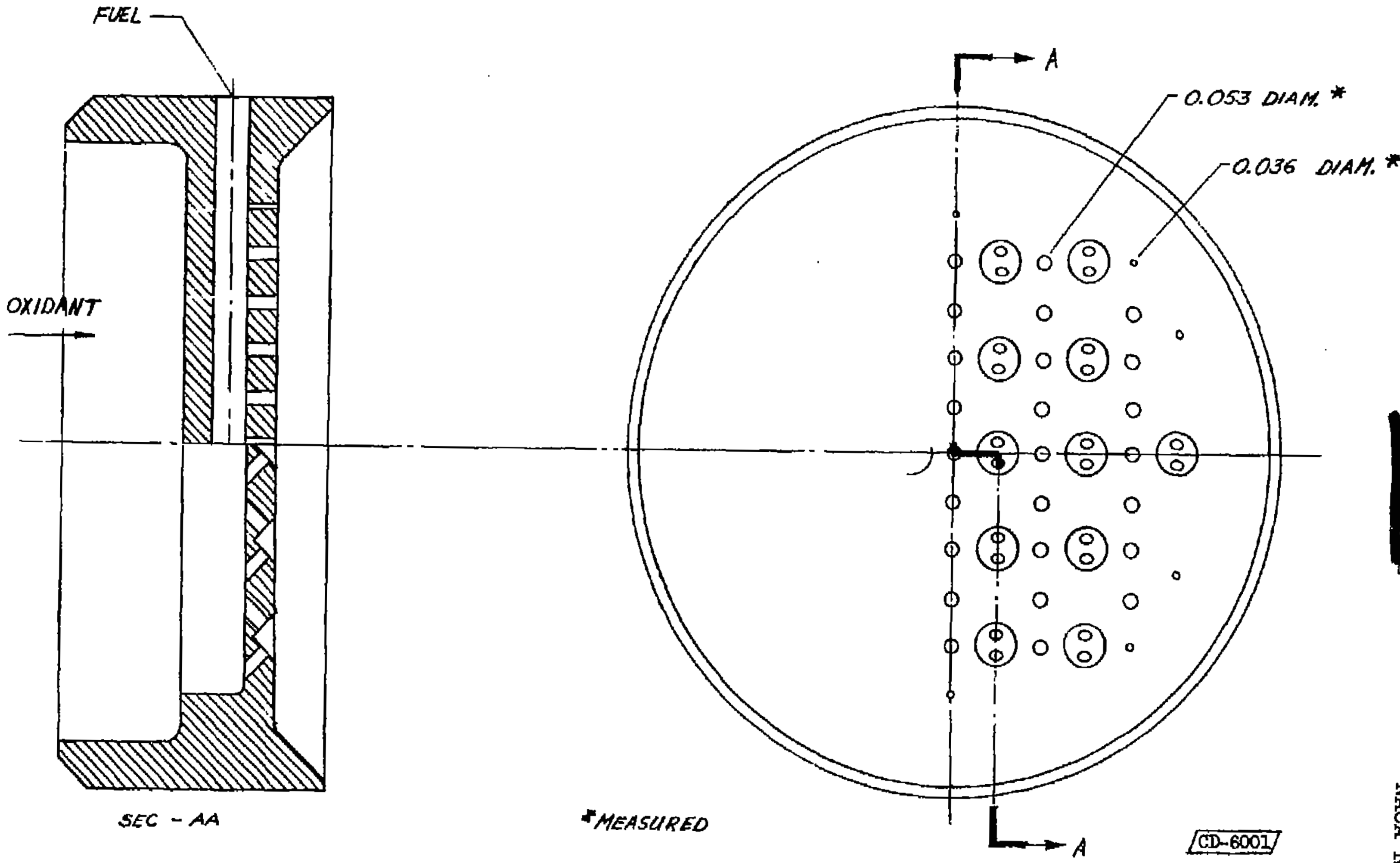
Figure 1. - Injector design. (All dimensions in inches.)

[redacted]



(b) RMI-2 injector; 22 pairs of like-on-like fuel holes with surface impingement at 90°; 22 showerhead oxidant holes.

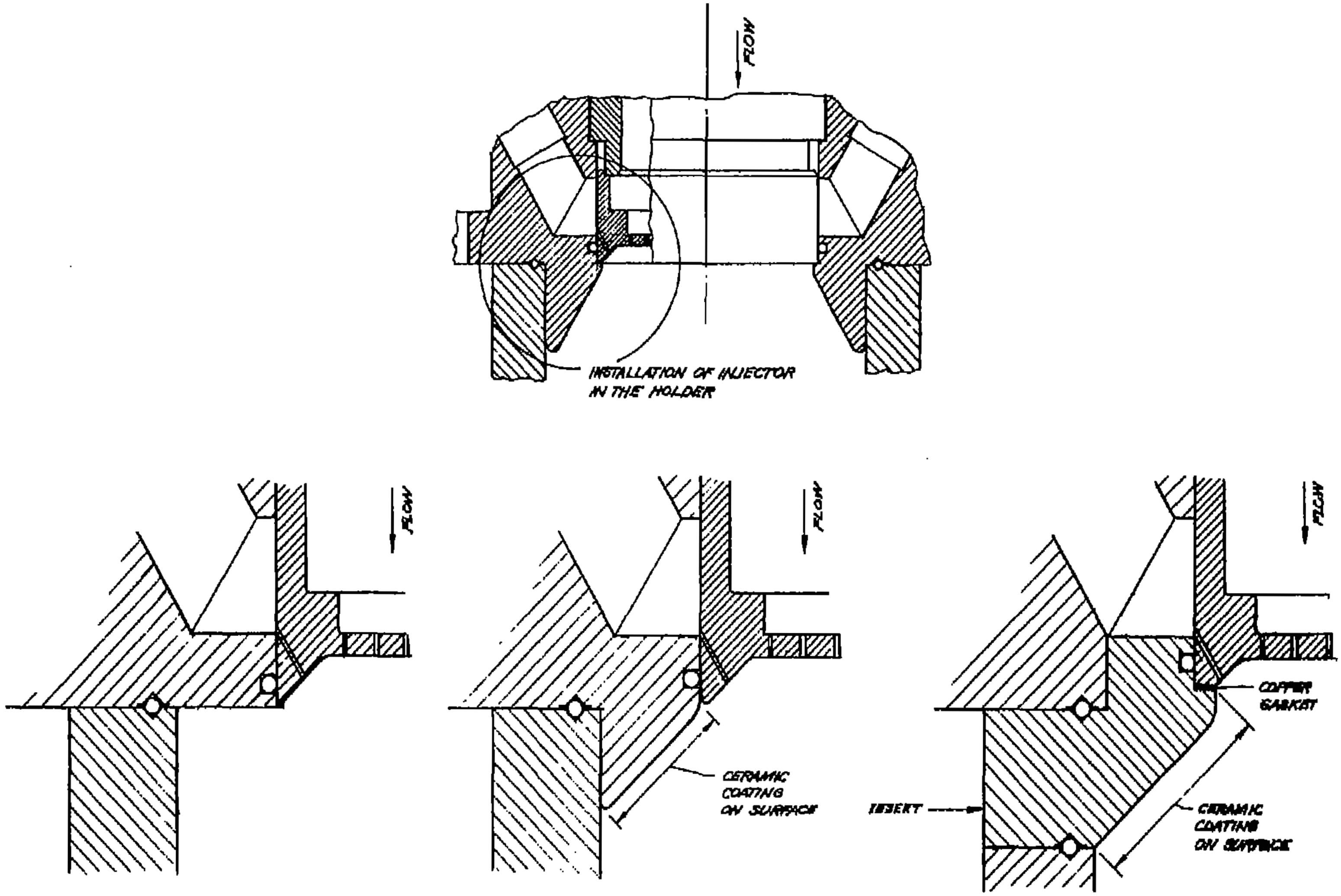
Figure 1. - Continued. Injector design. (All dimensions in inches.)



(c) RMI-3 injector; 22 pairs of like-on-like oxidant holes with surface impingement at 90°; 22 showerhead fuel holes.

Figure 1. - Concluded. Injector design. (All dimensions in inches.)

[redacted]



(a) Holder A. (b) Holder B. (c) Holder C.

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Figure 2. - Holder and injector modifications; injector rotated 90°.
(See fig. 3 for holder D.)

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[redacted]

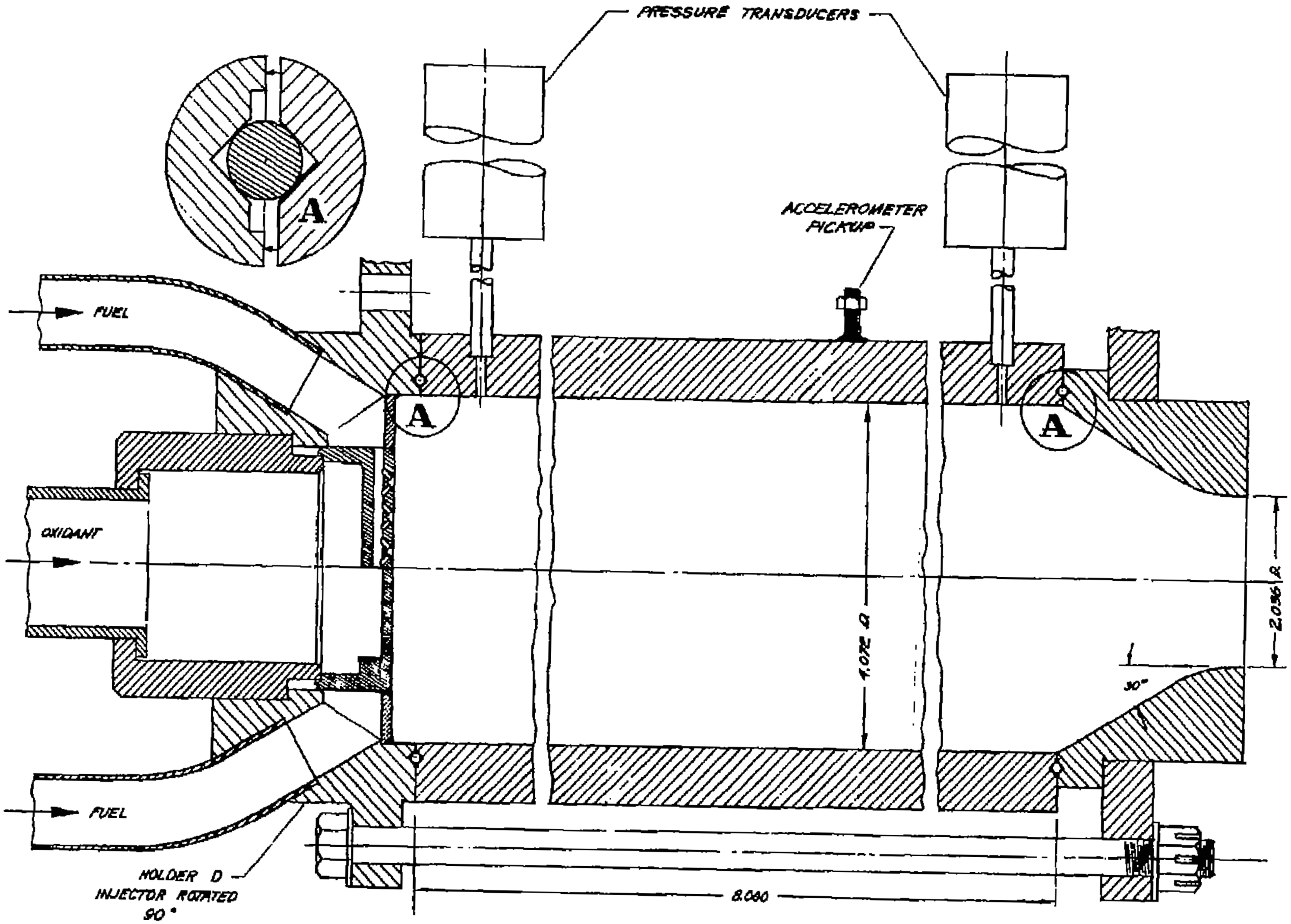

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Figure 3. - Engine assembly. (All dimensions in inches.)

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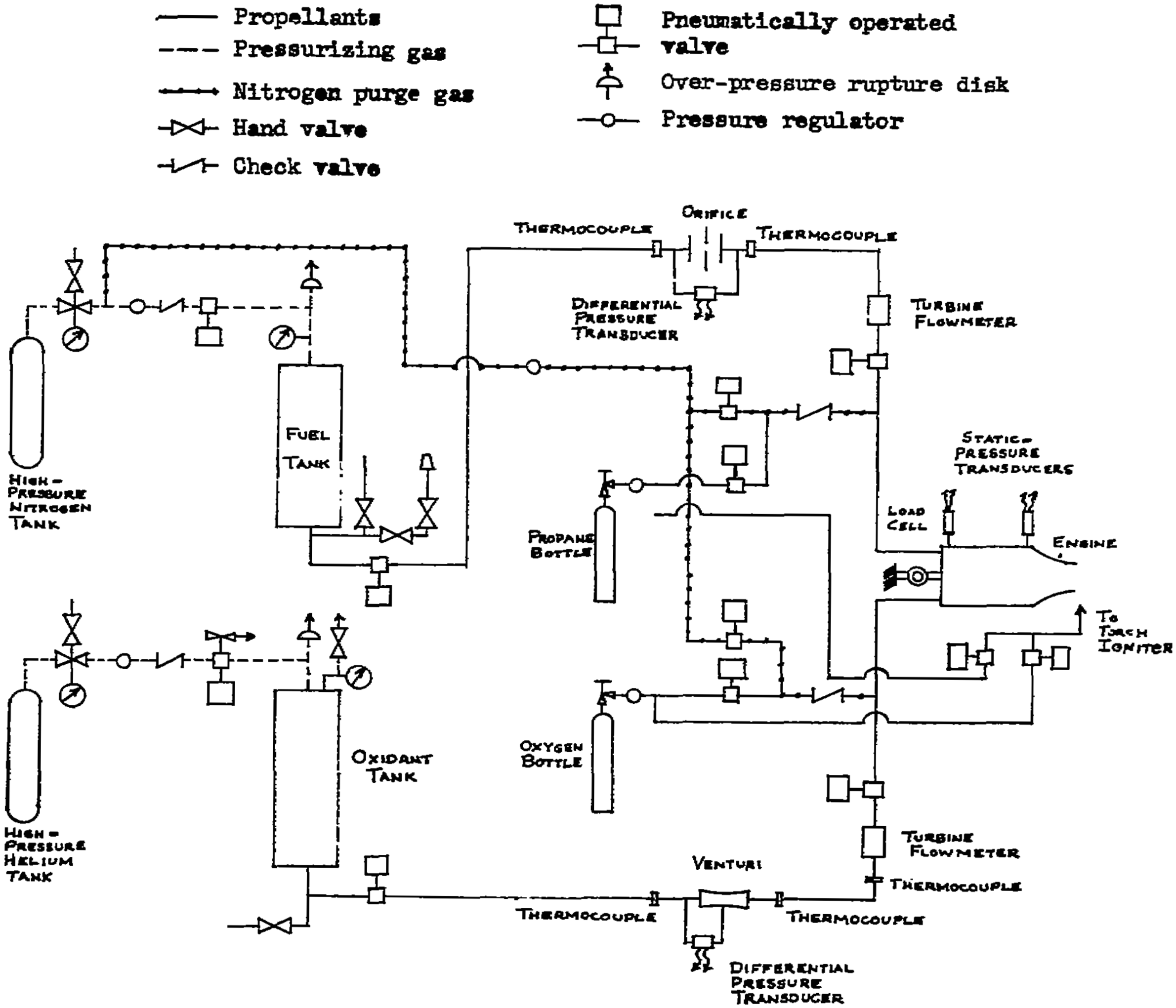

Figure 4. - Schematic diagram of test facility.

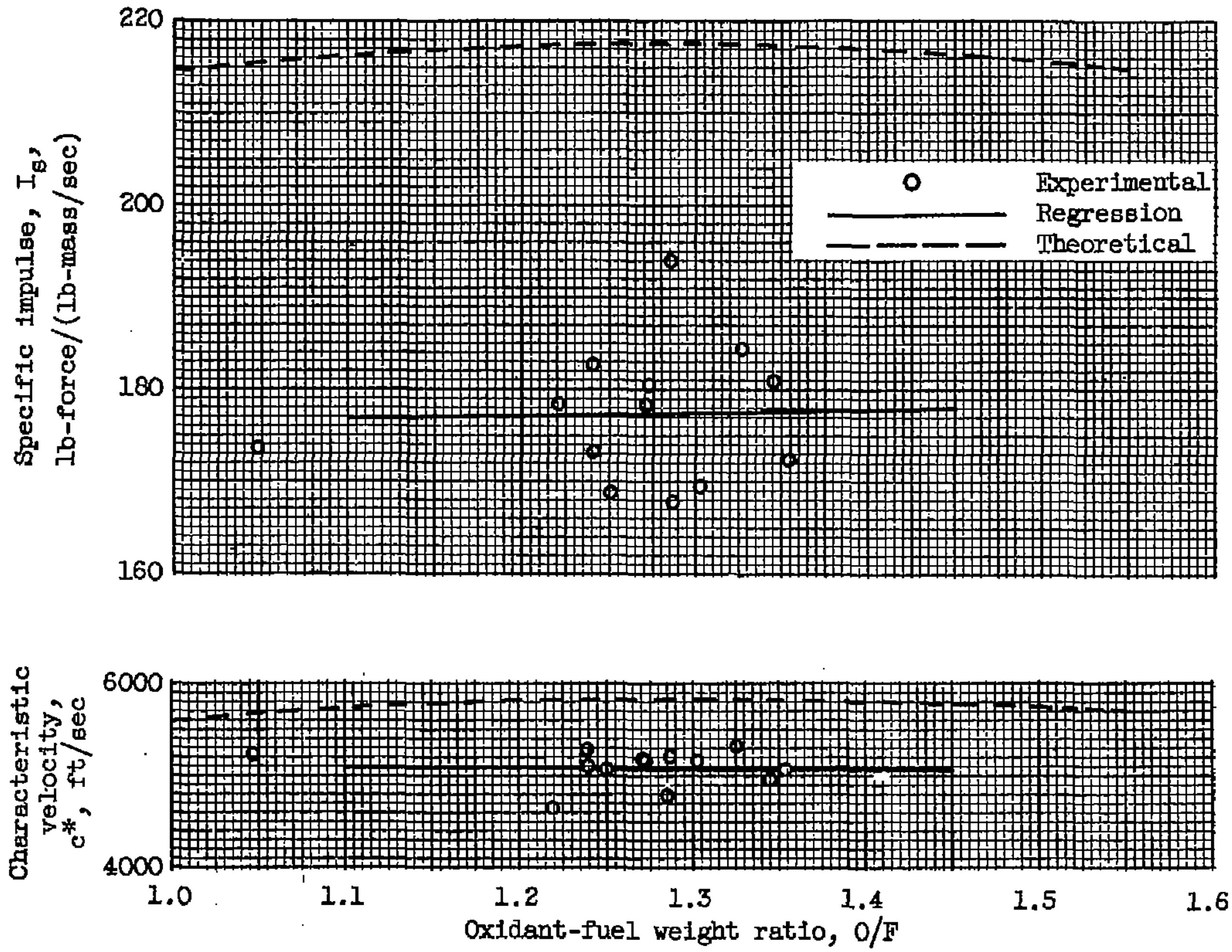

Figure 5. - Performance of RMI-1 injector. Fuel and oxidant like-on-like impingement.

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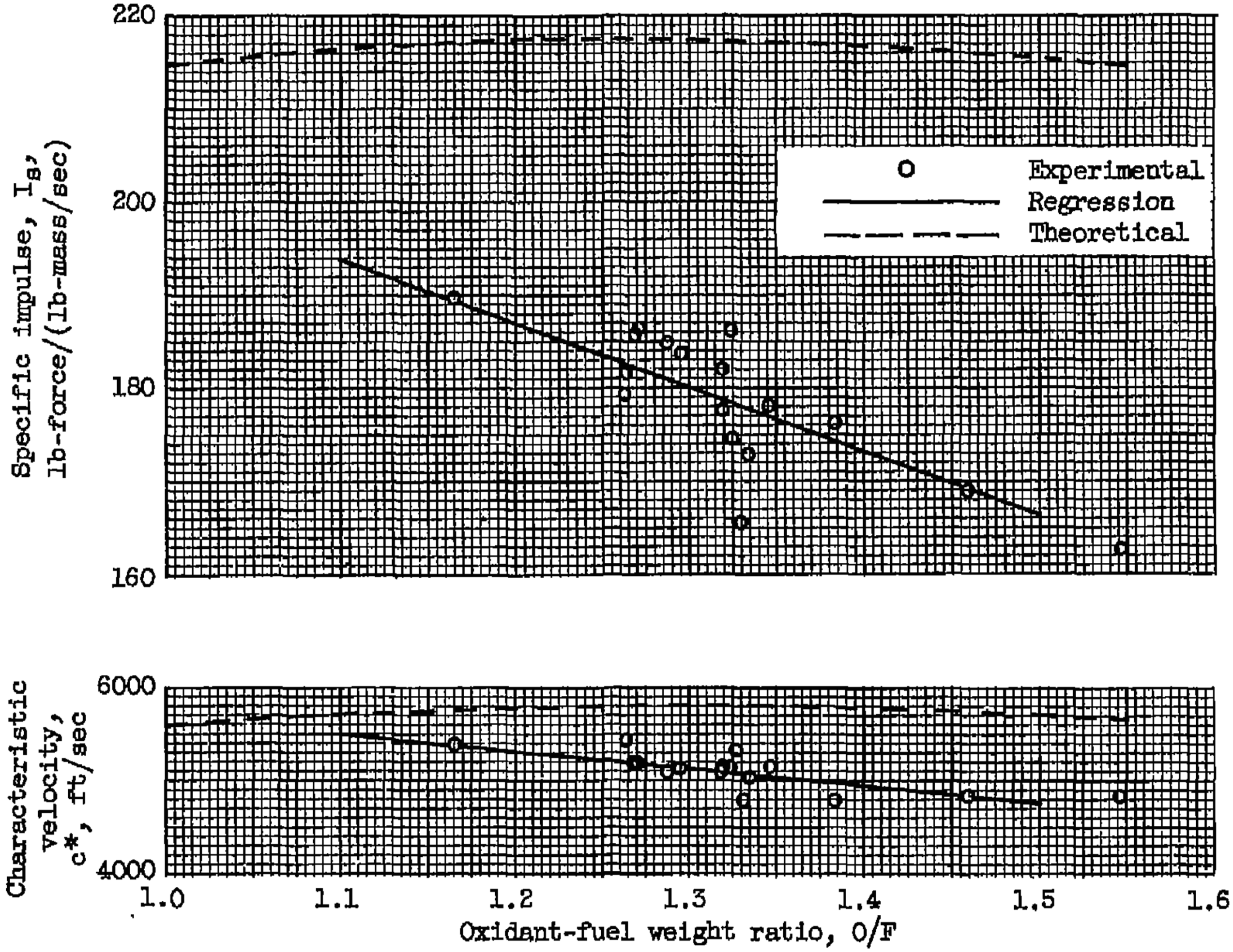

Figure 6. - Performance of RMI-2 injector. Fuel like-on-like impingement; oxidant showerhead.

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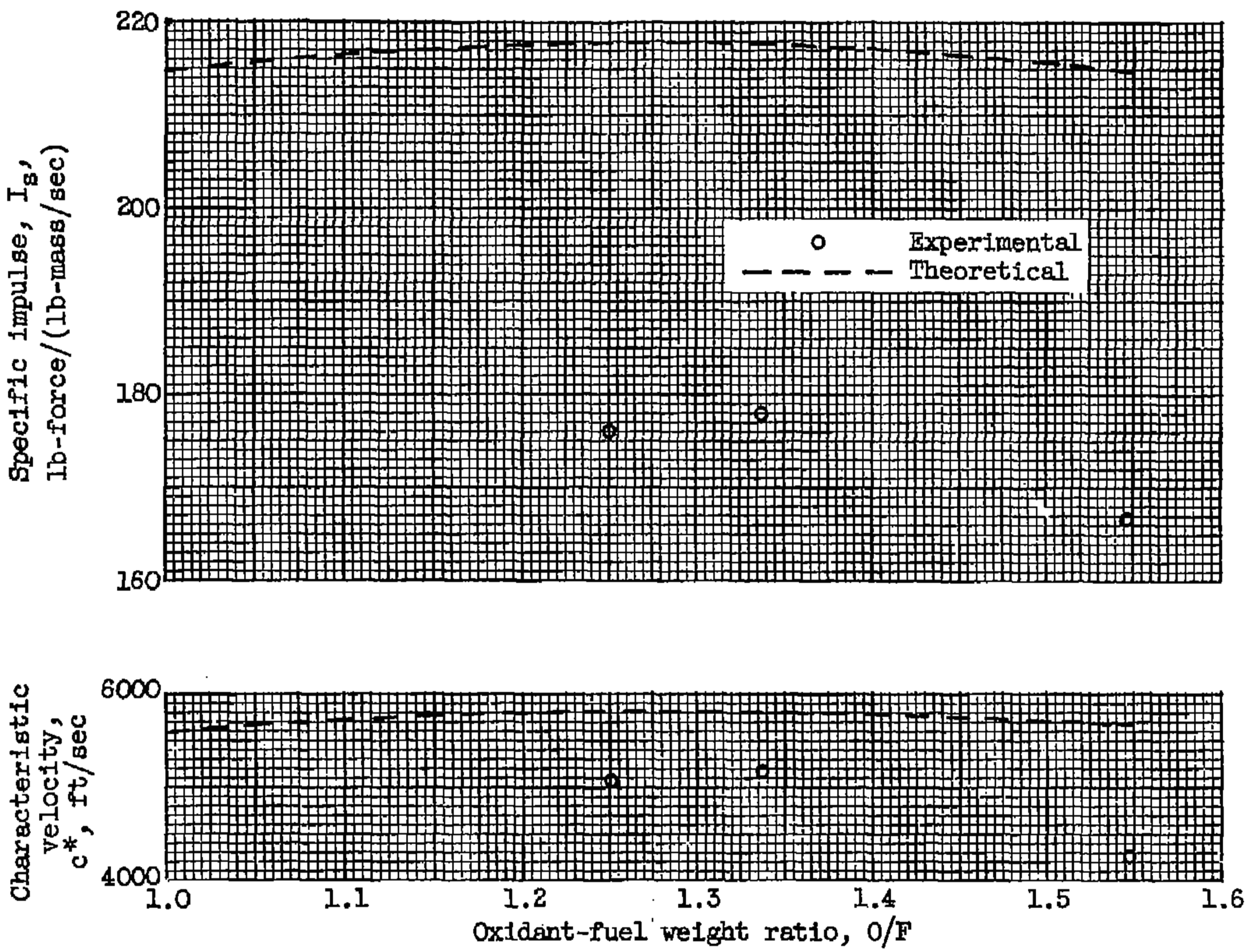

Figure 7. - Performance of RMI-3 injector. Oxidant like-on-like impingement; fuel showerhead.

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